3D PRINTING

THIRD EDITION

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THE REVOLUTION CONTINUES

The 3D Printing Revolution is starting to materialize. According to market research group CONTEXT, in 2015 the 500,000th 3D printer was shipped, with the millionth unit expected to be sold in 2017. 3D printing is also just starting to be adopted as an end-use manufacturing technology. For example, in 2016 GE began selling an aircraft engine with 3D printed fuel nozzles, an Atlas V rocket launched into space with 3D printed parts, both Under Armour and New Balance sold small batches of partially-3D-printed sports shoes, and Organovo started to commercially 'bioprint' human kidney tissue. Absolutely the 3D Printing Revolution is in its infancy. But very solid foundations continue to be laid.

Across history there have been many technological revolutions, all of which have progressed through three distinct phases. The first has been that of 'conceptualization', where visions and ideas have been generated that have defined the road ahead. Each technological revolution has then entered a phase of 'realization', during which time apparently impossible ideas have started to be turned into at least some form of operational reality. Finally we have arrived at a phase of 'mass commercialization', where businesses have learnt how to manufacture and operate a new technology in a robust and highly cost-effective manner.

So where does 3D printing sit on the technological revolution continuum? Well, today the idea of using a 3D printer to turn a digital file into a physical object has propagated widely and is well understood. Indeed across disciplines as diverse as engineering, law, economics, business, geography and fine art, there is already much debate concerning the potential implications of being able to routinely share objects across the Internet for 3D printout on demand. Clearly we are a very long way from the day in which personal 3D fabricators may bring capitalism to an end by putting the means of production into the hands of the majority. Yet there can be no doubt that the 3D Printing Revolution has already been rigorously *conceptualized*.

Further, we have already invented a fairly wide range of methods for fabricating solid objects by printing them out in many thin, successive layers. In fact, the most established 3D printing technologies have been around for decades. The 3D Printing Revolution is therefore making at least some progress when it comes to its practical *realization*.

While 3D printing continues to advance, I would contend that it is still at least ten years away from its final revolutionary phase of *mass commercialization*. Granted, as we shall see across this book, 3D printing pioneers are now using the technology to fabricate all kinds of things. Yet right now – at least as an end-use manufacturing process – 3D printing remains limited in its commercial application to a few niche markets. Specifically, these are sectors that are prepared to pay a premium to engage in low-run, customized or personalized production, or to manufacture items that cannot be made using traditional methods.

The above point noted, we should remember that a decade ago no industrial sector was reporting the sale of final products made in whole or part using a 3D printer. The fact that this is now occurring in *any* marketplace is therefore impressive. As new 3D printing methods are developed, and

as older processes become faster and cheaper, we should therefore expect 3D printing to accelerate toward mass commercialization in the late 2020s or early 2030s. The most innovative pioneers are also set to take advantage of 3D printing well before that.

3D PRINTING TECHNOLOGIES

So how, you may be wondering, does 3D printing actually work? Well, to a large extent, the processes involved are no more than a logical evolution of the 2D printing technologies already in use in a great many offices and homes.

Most people are familiar with the inkjet or laser printers that produce most of today's documents or photographs. These create text or images by controlling the placement of ink or toner on the surface of a piece of paper. In a similar fashion, 3D printers fabricate objects by controlling the placement and adhesion of successive layers of a 'build material' in 3D space. It is indeed for this reason that 3D printing is also known as 'additive layer manufacturing' (ALM) or 'additive manufacturing' (AM).

To 3D print an object, a digital model first needs to exist in a computer. This may be created using a computer aided design (CAD) application, or some other variety of 3D modelling software. Alternatively, a digital model may be captured by scanning a real object with a 3D scanner, or derived from a 3D scan that is later manipulated with CAD or other software tools.

Regardless of how a digital model comes into existence, once it is ready to be fabricated it needs to be put through some 'slicing software' that will divide it into a great many cross sectional layers that are typically about 0.1 mm thick. These digital slivers are then sent to a 3D printer that fabricates them, one on top of the other, until they are built up into a complete 3D printed object. Figure 1.1 illustrates a 3D model in the popular, open-source slicing software Cura,

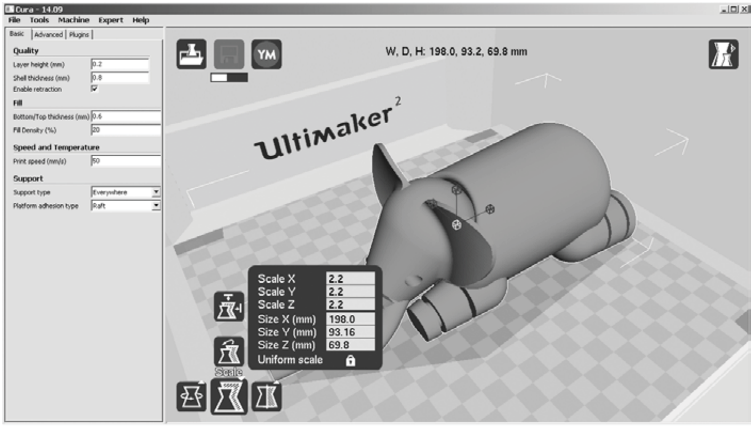

Figure 1.1: A 3D Model in the Cura Slicing Application.

while figure 1.2 shows the same model being fabricated on an Ultimaker 2 desktop 3D printer.

Exactly how a 3D printer outputs an object one thin layer at a time depends on the particular technology on which it is based. As I shall explain in depth in chapter 2, already there are a great many 3D printing technologies. This said, most of them work in one of four basic ways.

Firstly, there are 3D printers that create objects by extruding a molten or otherwise semi-liquid material from a print head nozzle. Most commonly this involves extruding a molten thermoplastic that very rapidly sets after it has left the print head. Other extrusion-based 3D printers manufacture objects by outputting molten metal, or by extruding chocolate or cake frosting (icing) to 3D print culinary creations. There are also 3D printers that extrude concrete, a ceramic paste or clay.

A second category of 3D printer creates object layers by selectively solidifying a liquid resin – known as a 'photopolymer' – that hardens when exposed to a laser or other light source. Some such 'photopolymerization' 3D printers

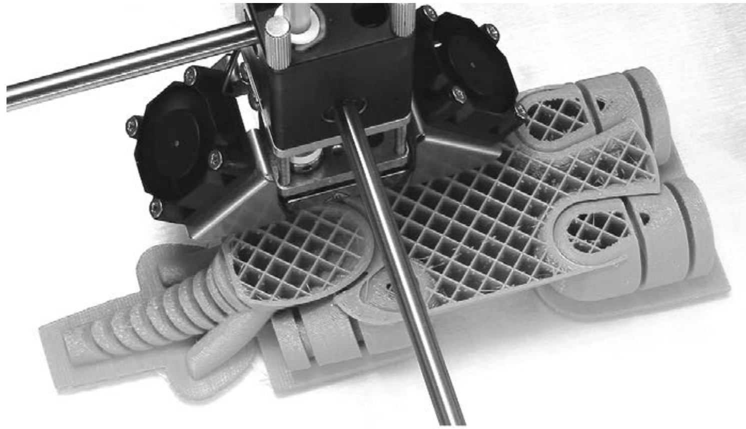

Figure 1.2: 3D Printing on an Ultimaker 2.

build object layers within a tank of liquid. Meanwhile others jet a single layer of resin from a print head and use ultraviolet light to set it solid before the next layer is added. A few of the 3D printers based on the latter technology are able to mix several different photopolymers in the same print job, so allowing them to output colour objects made from multiple materials. Most notably, the latest such 3D printer – the J750 from Stratasys – offers a palette of 360,000 colour shades, and can fabricate objects in a mix of different materials including 'rubber-like' and 'digital ABS'.

A third and very broad category of 3D printing hardware builds object layers by selectively sticking together the granules of a very fine powder. Such 'granular materials binding' can be achieved by jetting an adhesive onto successive powder layers, or by fusing powder granules together using a laser or other heat source. Various forms of powder adhesion are already commonly used to 3D print in a wide range of materials. These include nylon, wax, bronze, stainless steel, cobalt chrome and titanium.

A final category of 3D printer is based on lamination. Here, successive layers of cut paper, metal or plastic are stuck together to build up a solid object. Where sheets of paper are used as the build material, they are cut by blade or laser and glued together. They may also be sprayed with multiple inks during the printing process to create low-cost, full-colour 3D printed objects.

MARKETS & APPLICATIONS

3D printing is already being used to build product prototypes, to make molds and other industrial tooling, for the 'direct digital manufacture' of final products, and for personal fabrication. This means that hardware, software and material suppliers within the 3D printing industry are already serving the needs of four different market sectors. To truly appreciate the forces driving the 3D Printing Revolution, an understanding of the four different areas of 3D printing application is therefore required.

Rapid Prototyping

Today, 3D printers are most commonly used for rapid prototyping (RP). This is where the hardware is employed to create either concept models or functional prototypes. Concept models are usually fairly basic, non-functional printouts of a new product design (for example a shampoo bottle without a removable top), and are intended to allow designers to communicate their ideas in a physical format. In contrast, functional prototypes are more sophisticated, and allow the form, fit and function of each product part to be accurately assessed before committing to production.

Traditionally, prototypes and concept models have been created by skilled craftspeople using labour-intensive workshop techniques. It is therefore not uncommon for them to take many days, weeks or even months to produce, and to cost thousands or tens of thousands of dollars, pounds,

euro or yen. In contrast, 3D printers can now produce concept models and functional prototypes in a few days or even a few hours for a fraction of the price of traditional methods. Industries that make extensive use of 3D printing to create prototypes include automobile manufacture and Formula 1.

In addition to saving time and money, the 3D printing of prototypes allows improved final products to be brought to market, as designs can evolve through a great many iterations. For example, vacuum flask manufacturer Thermos now uses Stratasys 3D printers to make its own prototypes in hours rather than days, and for a fifth of the cost of outsourcing their production to an external vendor. Because its designers are now free to 'make as many prototypes as they need', the company has been able to optimize product features such as cap-fit and pouring performance.

As capabilities to 3D print in colour, in multiple materials, and in metals, continue to improve, so the range and quality of products and components that can be rapidly prototyped continues to expand. As illustrated in figure 1.3, a company called Nano Dimension has even showcased a new desktop 3D printer – the DragonFly 2020 – that can fabricate functional, prototype 3D printed circuit boards. This amazing hardware uses an inkjet technology to output highly conductive 'nano-inks', and can produce multilayer boards, including all interconnections between layers. While currently many companies wait many days or weeks to obtain a prototype circuit board from an external vendor, the DragonFly 2020 can 3D print one in a matter of hours.

Producing Molds & Other Tooling

In addition to rapid prototypes, 3D printers are increasingly being used to make molds, jigs, fixtures and other production tooling. Most production processes require such items to be created in order to fashion metals or plastics into final

Figure 1.3: The DragonFly 2020 Circuit Board 3D Printer.
Image courtesy of Nano Dimension.

product parts. Like product prototypes, molds and other production tooling have traditionally been painstakingly crafted by hand. The use of 3D printers to help tool-up factories for traditional production may therefore save a great deal of time and money. For example, by employing Stratasys Fortus 3D printers, Volvo Trucks in Lyon, France have reduced the time required to manufacture some of their engine assembly tools from 36 days to 2 days.

Equally demonstrating the extraordinary potential, in August 2016 the Oak Ridge National Laboratory in the United States 3D printed a 5.34 x 1.34 x 0.46 m (17.5 x 4.4 x 1.5 foot) trim-and-drill tool for Boeing. This will be used during the construction of the aircraft manufacturer's forthcoming 777X passenger jets, and was 3D printed in a carbon fiber reinforced plastic in about 30 hours. In contrast, the existing metallic tooling option for the part would have taken three months to manufacture. As Boeing's Leo Christodoulou explained, 'additively manufactured tools, such as the 777X wing trim tool, will save energy, time, labor and

production cost and are part of our overall strategy to apply 3D printing technology in key production areas'.

Another particularly promising application is in the production of the molds used in traditional metal casting. Here 3D printers can directly produce the required molds, as well as any of the additional 'core' shapes required to fit inside them, by laying down thin layers of casting sand that are then selectively sprayed with a binder. The resultant 3D printouts are taken to a foundry, where molten metal is poured in to produce final components.

One of the companies that specializes in making 3D printers that additively manufacture in casting sand is ExOne. As they report, by 3D printing sand cast molds and cores, manufacturers can not only save time and reduce costs, but may also improve accuracy and cast more intricate parts. This is because the production of 3D printed molds and cores does not depend on packing sand around a physical 'pattern', which then needs to be removed without inflicting damage. Figure 1.4 shows a sand casting core produced on an ExOne 3D printer.

3D printers can now also be used to fabricate the molds used to injection-mold plastic parts. Such molds typically cost tens of thousands of dollars, and are traditionally machined from aluminium. Technically, it is now possible to make aluminium injection molds using a direct metal, powder-based 3D printer. However, at least at present, 3D printers are more commonly used to make low-run injection molds from resin using photopolymerization hardware. Resin molds are inevitably not as hard-wearing as their aluminium counterparts. They are, however, cheaper and quicker to fabricate, and may be used to produce up to about 200 plastic parts before they need to be replaced. Figure 1.5 shows a two-part, 3D printed resin injection mold created on a Stratasys 3D printer.

Just one company now benefitting from the ability to 3D print low-run, resin injection molds is Bi-Link, based in

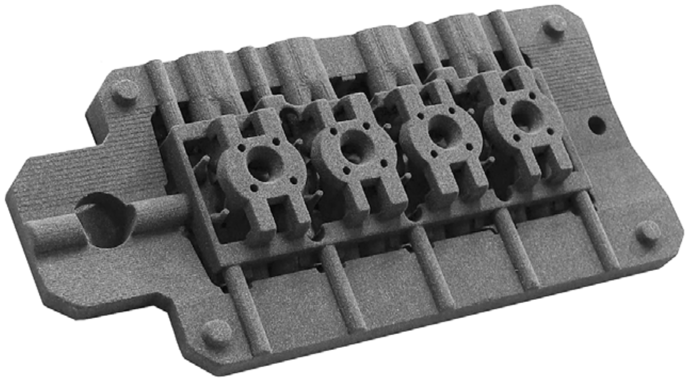

Figure 1.4: A 3D Printed Sand Casting Core.

Bloomingdale, Illinois, which makes parts for electronics and medical manufacturers around the world. Here a ProJet 3500 HD Max 3D printer from 3D Systems is used to make molds in hours rather than weeks. As noted by R&D Director Frank Ziberna, ‘customers love this service. They would typically have to wait two to three weeks to get just tooling, never mind test parts. With the ProJet 3500 HD Max we made one customer four different part designs over the course of six days, shipping them 10-12 [injection-molded] parts for each iteration overnight’.

Several manufacturers now also produce 3D printers that can build objects in wax (or wax substitutes) in order to create patterns for lost-wax casting. Here, a wax object is 3D printed, and a mold is formed around it using a material such as plaster. The mold is then heated, which causes the wax to ‘burnout’ and drain away. Molten metal, or another liquid casting material, is subsequently poured into the mold to produce the final item. Using 3D printers to make lost-wax patterns is now fairly common in jewelry making and other industries in which small, intricate, high-priced objects need to be manufactured. Like sand cast molds, lost-wax 3D

Figure 1.5: A 3D Printed Resin Injection Mold.

printed patterns are ‘sacrificial’, as the process of producing a final object from them results in their destruction.

Direct Digital Manufacturing

As I showcased at the start of this chapter, in a few niche markets 3D printers are already being used to manufacture end-use industrial components and even final consumer products. This exciting development is increasingly referred to as ‘direct digital manufacturing’ (DDM), and is gaining significant traction in aviation in particular. Indeed, as we shall see in chapter 4, Airbus, Boeing and GE have now collectively installed tens of thousands of 3D printed aircraft components.

Other sectors at the forefront of DDM include automobile manufacture, medicine, jewelry making, and the production of specialist footwear. Here one of the leading pioneers is Nike, which in October 2015 announced that it was ‘turbo charging’ its 3D printing efforts. Indeed, to cite Chief Operating Officer Eric Sprunk, Nike has ‘made a series of design and manufacturing discoveries with 3D printing that we believe will allow us to deliver a completely new, personal, performance cushioning system'. To this end, a 125,000-square-foot Advanced Product Creation Center is being built at Nike's headquarters to house 3D printing and other advanced design and manufacturing technologies.

In the future, it is possible that almost anything could be manufactured using a 3D printer, and that even includes replacement parts for ourselves. Most prominently at present, dentistry is 'going digital', with wax-ups, orthodontic appliances, try-ins, surgical guides and veneer models now routinely 3D printed.

Beyond the creation of inorganic prosthesis, there are already also specialist 3D printers that can build up human tissue by laying down layer-after-layer of living cells. Such 'bioprinters' have the potential to transform many areas of medicine, and may cut organ donor waiting lists to zero. Already a bioprinting pioneer called Organovo is selling bioprinted human liver and human kidney tissues as commercial products for use in drug testing.

In addition to 3D printing human tissues outside of the body, *in vivo* bioprinting is also in development. This involves 3D printing layers of cultured cells directly onto a wound, or even inside the body using keyhole surgery techniques. Should this kind of technology become advanced enough, one day instruments may be able to be inserted into a patient that will remove damaged cells and replace them with new ones. Such instruments may even be able to repair the wound created by their own insertion on their way out. I will explore bioprinting in depth in chapter 6.

Personal Fabrication

In parallel with the growth of industrial 3D printing, we are starting to witness the rise of personal fabrication. This refers to all situations in which individual 'makers' 3D print their own stuff, so by-passing the need for everything they own to have started life in a distant factory. As we shall see in chapter 5, already there are several hundred personal and prosumer 3D printers on the market, with prices starting at around $230.

In addition to the growing number of personal 3D printers, there is also an increasing provision of free or for-a-fee 3D models that can be downloaded for personal printout. Chief among the providers of free content is Thingiverse, which hosts over a million 3D objects, some of which can be customized to user specification. The provision of online 3D content is likely to be key to any mass uptake of personal fabrication, as it removes the need for all makers to possess a raft of creative, CAD and engineering skills.

Right now, personal and prosumer 3D printers are limited to fabricating objects in thermoplastics, thermoplastic composites and sometimes photocurable resins. The range and quality of items that can be personally fabricated on such hardware therefore remains limited. This said, an increasing number of 3D printing services – such as Shapeways and i.materialise – now allow anybody to upload a 3D object that they will 3D print for them on industrial hardware. Over the next five-to-ten years, it is also likely to be the broadening availability of such 3D printing services – and not the sale of personal 3D printers – that will drive any revolution in personal manufacturing.

If a reasonable proportion of people do start to fabricate some of their own possessions, the impact on some industries could be very significant. Not least companies that trade in spare parts are already starting to take the threat of mass personal fabrication extremely seriously. So too are those in the logistics and transport sector who may experience a change in demand for their services.

In an attempt to map out the road ahead, in 2014 the IBM Institute for Business Value published an Executive Report that highlighted four distinctly different futures for personal fabrication. These it encapsulated in a 2x2 matrix, which I reproduce in an adapted and augmented format in figure 1.6.

As the figure suggests, the two great unknowns (which constitute the two axes of the matrix) are the speed at which 3D printing technology will develop, and the willingness of end consumers to embrace personal fabrication. To work through the possible scenarios, if technology improves slowly and end-consumers are unwilling to embrace 3D printing in the home, then we will see little more than a ‘quiet revolution’ with only incremental change. Alternatively, if technology improves slowly but many end-consumers are keen to become makers, then we will see a ‘print shop renaissance’, with an increasing number of our possessions personally-fabricated by a bureau service.

Looking to the right side of the matrix, if 3D printing technology improves rapidly but consumers remain ambivalent, then 3D printing will become a major industrial manufacturing technology, but will have little impact on the consumer marketplace. Finally, if 3D printing technology improves rapidly and end-consumers choose to engage with it in significant numbers, then we will witness the ‘reinvention of consumption’. This means that we would see retailers large and small offering products 3D printed on demand, as well as many people 3D printing their own stuff in their kitchens, dens, garages, offices and sheds.

Right now, my hunch is that end-consumer engagement with 3D printing will rise in step with technological improvement, if at a slower rate. This means that, over the next few decades, we may progress from IBM’s ‘quiet revolution’, across into a ‘manufacturing revolution’, and up into a ‘reinvention of consumption’ as I have indicated in the diagram.

3D PRINTING INDUSTRY DEVELOPMENT

Staying with the theme of how the 3D Printing Revolution may potentially unfold, it is important to appreciate not just

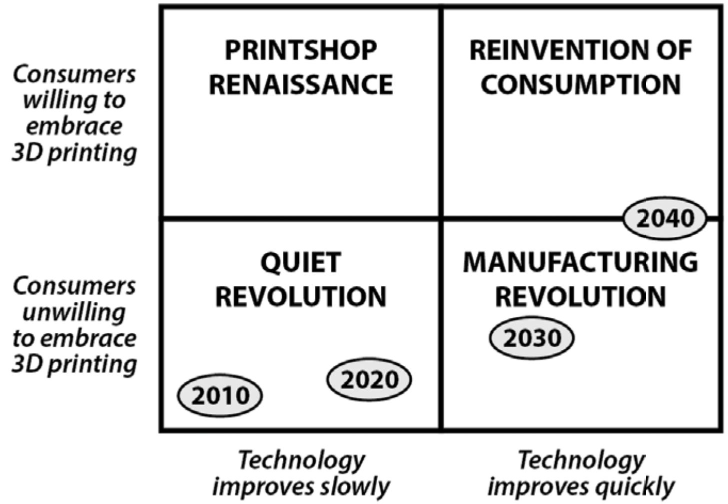

Figure 1.6: The Future of Personal Fabrication.
Adapted from IBM Institute for Business Value (2014).
Date augmentations by Christopher Barnatt.

the existence of the 3D printing industry’s four, distinct market segments, but also the fact that they are all in very different stages of development. To highlight this frequently ignored reality, figure 1.7 plots four curves that are indicative of the different rates of 3D printing adoption for rapid prototyping, the production of molds and other tooling, direct digital manufacturing, and personal fabrication. As you will see, each adoption curve conforms to a well understood pattern in which use rises exponentially from zero, achieves consistent growth, and then falls away as application approaches market saturation.

The adoption curves plotted in the figure are based on my own industry analysis, and are intended to assist our understanding of likely 3D printing development. Not least, they remind us that while the very first 3D printers started to be used to make product prototypes in the late 1980s, the use of 3D printing to create molds and other tooling did not commence until a few years after that. It was then not until the turn of the millennium that anybody started to make end-use components or works of art using 3D printers. Finally, personal fabrication only became a possibility around 2007 with the development of the first 'open source' 3D printers that private individuals could afford to own.

As figure 1.7 suggests, my personal best-guess is that by mid-next-decade, the traditional 3D printing market segment of rapid prototyping will saturate, with maybe half of all concept models and prototypes being 3D printed by 2025. Some may question why I have this adoption curve maxing out at 50 per cent market penetration. But I think this is realistic for two reasons. Firstly, 3D printing is not the only rapid prototyping technology. And secondly, there will always be instances where traditional methods will remain the most appropriate for prototype production. I simply cannot imagine a time when inventors will stop mocking things up out of bits of wood, card, metal, clay, and anything else they happen to have to hand in their studios, labs, workshops, sheds or kitchens.

Turning to the 3D printing of molds and other tooling, this market currently lags behind rapid prototyping, but is set to become a mainstay of additive manufacturing very soon indeed. As figure 1.7 indicates, my prediction is that it will take decades for this market to saturate. Talk to industrial 3D printer manufacturers, and they are also well aware of this. Right now, in most industries, the 3D printing of molds and other tooling represents the largest market opportunity.

Moving on to direct digital manufacturing, as we have already seen this is just starting to take place, if currently as a very niche activity. However, in the next ten years or so, many industries – most notably including aerospace, the au-

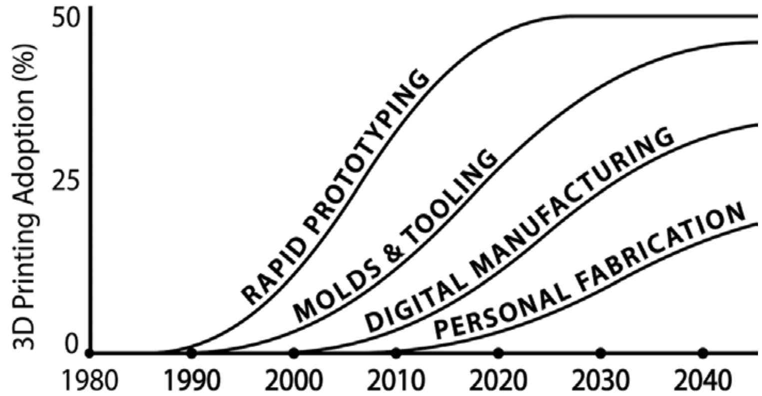

Figure 1.7: 3D Printing Adoption Curves.

tomotive sector, healthcare, fashion, footwear and designer goods – are set to embrace 3D printing as one of their core manufacturing technologies. This will undoubtedly allow entirely new kinds of products to be created, and will garner popular media attention. Even so, in 10 or 20 years time, the vast majority of the objects in our lives will still be produced via traditional methods, if often using 3D printed molds, jigs and other tooling.

In a similar fashion, for many decades personal fabrication will remain a niche if fascinating market segment, and a small proportion of both the 3D printing industry and total global manufacturing. Right now, no more than 10 per cent of 3D printing industry revenues are generated via the sale of personal 3D printers. Many such printers are also sold to companies, not individuals. This is not to suggest that the sale of personal 3D printers for use in the home does not represent a significant market opportunity, with the annual global sale of around 500,000 consumer-grade 3D printers by 2020 being a very reasonable prediction. But this point noted, by 2020 the average personal 3D printer will probably cost under $1,000, so making the annual sale of 500,000 units worth less than $500 million. This means that, by 2020, personal 3D printing will account for no more than a few per cent of a global 3D printing market that will probably be worth well in excess of $10 billion, and perhaps as much as $20 billion.

Due to the above, I feel very safe in my prediction that domestic personal fabrication is not going to be the driving force behind the 3D Printing Revolution – and I do not know a serious industry participant who does not agree with me on this one. I am, nevertheless, very much looking forward to the $99 3D printers that will be on the market by 2020, and which will be able to fabricate small, plastic objects beamed to them from a tablet or smartphone.

MAKING NEW THINGS IN NEW WAYS

Just like the Internet Revolution that preceded it, the 3D Printing Revolution will increasingly allow both companies and individuals to achieve the previously impossible. This is because 3D printing will enable us not just to prototype and manufacture old things in new ways, but to create and deliver new products in new ways according to radically new business models. Just how this will happen is in effect the subject of chapters 3 to 7 of this book. But before we get there, it is worth signalling those key opportunities that I have not yet highlighted in this chapter.

One-Off & Low-Run Production

Using traditional manufacturing methods, one-off or low-run production is usually very expensive, and often prohibitively so. In contrast, when things are 3D printed there is virtually no cost difference per item between making 1 or 100 or 1,000 copies of a component, as there are no tooling costs and few if any learning curves for production workers to climb. In many situations where a few hundred

or less components are required, 3D printing is therefore already the most cost effective means of manufacturing, and often the *only* cost effective option. It is indeed for this reason that 3D printing has such a high level of adoption in rapid prototyping, and is finding increasing application in the production of molds and other tooling.

Already availing himself of 3D printing for one-off production is classic car enthusiast Jay Leno. As just one example, when some broken vents needed replacing on Jay's rare EcoJet concept car, he turned to 3D Systems who scanned the broken parts, mended them digitally in CAD software, and sent the resultant data to their Quickparts service provider. Here new vents were 3D printed in a lightweight, fiber-filled nylon material called DuraForm HST. This resulted in robust replacement parts that had a better strength-to-weight ratio than the broken originals.

Others using 3D printing for one-off or small batch production include those who make props for TV, film and theatre productions, SpaceX (who are 3D printing the engine chambers for their new Crew Dragon spacecraft), and NASA, who have 3D printed about 70 parts for their experimental human Mars rover.

Customization & Personalization

In addition to facilitating the small batch production of identical things, 3D printing is already allowing products to be both customized in accordance with their purchaser's tastes, and personalized to match an individual's physical requirements. For example, the Robot Bike Co. now use 3D printing to help them manufacture their custom-fit R160 mountain bike frame. This is made from carbon fibre tubing that extends between titanium lugs that are additively manufactured on Renishaw 3D printers. Over on Robotbike.co, purchasers enter their height, inside leg and arm span measurements, which enables a custom-fit frame to be produced.

The R160 is a great example of a real product that combines custom 3D printed parts with other standard components in order to deliver a product to individual specification in a cost-effective manner. In time, I am certain that many other manufacturers will realize the potential to create bespoke products by 3D printing certain key parts. The more you think about it, the possibilities are very significant indeed.

Optimizing Design & Assembly

Another key benefit of 3D printing is that it relaxes the inevitable and long-standing constraints of traditional production methods. Today, while a designer can come up with any design they like, if its components cannot be cast, molded, machined and assembled, the product will never arrive on the market. But in the Brave New World of 3D printing, it is now possible to make things that were previously impossible to manufacture. For example, a 3D printer can make a chain or necklace made up of links that do not have a break in them, and which will therefore never come apart at a seam.

Highlighting the potential, a MotoGP World Championship motorcycle racing team called TransFIORmers have used a Renishaw direct-metal 3D printer to fabricate a new wishbone suspension with an optimized design. The original component was hand-fabricated in steel, with assembly requiring twelve separately machined parts to be welded together. But using 3D printing, TransFIORmers were able to consolidate their design into a single titanium component that required no assembly, and which resulted in a performance-critical 40 per cent weight reduction.

Using plastic or resin build materials, some 3D printers can even create working, pre-assembled, multipart mechanisms like gearboxes. Traditionally, the manufacture of multi-component products has had to involve a final assembly stage. But when things are 3D printed this no longer has to remain the case.

Democratizing Access to Market

In addition to improving the characteristics of the products that people purchase, 3D printing will additionally allow far more of us to actually become manufacturers. In part this is because the cost of making prototypes and production tooling will no longer prove prohibitive, with 3D printing making low-run production an increasingly viable proposition. Yet even more fundamentally, the increasing availability of 3D printing service bureaus will allow almost any talented artist or designer to find a market for their creations.

Today, it is very difficult for a private individual or even a small company to bring a product to market, let alone on a global scale. One of the few exceptions is in the world of book publishing, where a sole author – like myself – can create and distribute a product that is printed-on-demand. If, for example, you are reading this book in hardcopy, then you are currently holding a product that was printed in an Amazon warehouse within eight hours of it being ordered. This amazing innovation allows me to sell books worldwide without having to pre-print and distribute stock in the traditional manner.

In a similar fashion, 3D printing is starting to allow individual designers to bring products to market with no investment in capital equipment or stock. For example, over 8,000 designers have now opened a store via the website of the 3D printing service provider Shapeways. Just one of these is a self-described 'bot maker, guerrilla product developer [and] newbie modeller' who goes by the name of Kidmechano. His particular creation is 'Modibots', which is an ever-expanding range of highly poseable 3D-printed action figures with a snap-fit, ball joint construction. You can think of Modibots as a form of transformer-style, character building Lego.

Kidmechano uses the Shapeways platform to sell over 400 ModiBot figures and accessories, with these including a wide array of armour, weapons and stands. Prices start from a few dollars, and when an order is placed Shapeways 3D print whatever is required, ship the printouts to the purchaser, and provide Kidmechano with his share of the proceeds. Others using Shapeways to market, manufacture and ship their wares include the sculptress Bathsheba Grossman, who I interview in some depth in chapter 4.

Digital Storage & Transportation

As well as enabling low-run production, mass customization, and democratizing access to market, 3D printing will facilitate digital object storage and digital object transportation. What this means is that if, in the future, you want to send something to somebody far away, you will have two options. The first will be to despatch the physical item via courier or mail, while the second will be to send a digital file over the Internet for 3D printout at the recipient's location.

Many people now regularly share text, photos and video online, and thanks to 3D printing, digital objects will soon be added to many social media collections. By making possible online storage and transportation, 3D printing is therefore set to do for physical things what computers and the Internet have already done for the storage and communication of digital information.

In some industries, digital object storage is already starting to prove advantageous. Most dentists, for example, have traditionally had to store a great many plaster casts taken from impressions of their patient's mouths. While the vast majority of these have only ever been used once, there has been no way to predict which may be required for future reference, so leading to boxes and cabinets piled high with plaster models. But now dentists are going digital, with 3D scanners and 3D printers replacing alginate mold making materials and plaster casting. In turn, this is starting to allow impressions of patient's mouths to be stored digitally for future 3D printout only if required.

Material Savings & Sustainability

In addition to all of the aforementioned opportunities, some of the greatest benefits of 3D printing arise from material savings and the broader sustainability agenda. Today, a great deal of manufacturing is a subtractive process. In other words, factories start with a block of metal or another raw material, and then cut, lathe, file, drill or otherwise remove bits from it in order to fashion a final component. In contrast, 3D printing is an additive activity that starts with nothing and adds only the material that the final part requires. As a consequence, when things are fabricated using 3D printers it is possible to obtain very substantial raw material savings.

In addition, 3D printed products can feature internal structures that are optimized to consume the minimum of materials. 3D printed plastic or metal parts can, for example, be fabricated with internal air gaps or open lattice work that cannot exist inside an object produced using many traditional production techniques. This again can result in material savings, as well as the creation of lighter parts that can be used to make aircraft and other vehicles more fuel efficient.

More broadly, 3D printing may turn out to be the cornerstone of a future transition toward 'local digital manufacturing' (LDM). Today, a great deal of manufacturing takes place in factories that are far removed from most customers. As a consequence, vast quantities of oil and other resources are used to move products around the planet, with many goods spending the majority of their lives in transportation and storage. Given the increasing pressure on natural resource supplies – coupled with measures to try and mitigate climate change – within a decade or two such mass transportation and storage may be neither feasible nor culturally acceptable. Pressures to improve sustainability could therefore turn out to be the greatest force that will drive the mainstream adoption of 3D printing, as the technology will increasingly assist in the production of products on a far more local basis.

CHALLENGES AHEAD?

Like any new technology, 3D printing has the potential to be highly disruptive in negative as well as positive ways. Not least, there are already concerns that the further development of 3D printing will destroy manufacturing jobs. For those in some occupations this is indeed very likely to be the case, with employment certainly under threat for those who currently produce prototypes, molds and tooling via traditional methods.

Employment in nations who currently mass manufacture products for export is also likely to be reduced as and when 3D printing starts to facilitate more local production. Indeed, in his 2013 State of the Union address, President Obama highlighted 3D printing as the technology with 'the potential to revolutionize how we make almost everything', and in a manner that would bring manufacturing jobs back from Asia to the United States. Make no mistake, the global economic implications of 3D printing have already been recognized at the government level.

The above points noted, and in common with previous revolutionary technologies, 3D printing is likely to create new employment opportunities. It is going to be a very long time indeed before we can 3D print final products without significant, skilled human intervention. New kinds of manufacturing jobs will therefore be created as the 3D Printing Revolution takes hold, and such employment is likely to be fairly evenly spread across nations and their regions in a manner uncharacteristic of previous manufacturing revolutions.

Some non-manufacturing industries are also likely to benefit from the rise of 3D printing. Not least, parts of the logistics sector have started to recognize significant opportunities. For example, in July 2014 the Office of the Inspector General of the US Postal Service published a White Paper in which it noted that the postal service could 'benefit tremendously' from the rise of 3D printing due to an anticipated increase in the last-mile delivery of small packages. Specifically, the White Paper forecast that 3D printing could result in its local parcel delivery service experiencing revenue increases of $486 million every year. This projection was based on the proposition that most 3D printed goods will be manufactured in relatively local service bureaus, from where they will need transporting to people's homes.

Beyond the impact on employment, two other challenges are intellectual property infringement and the use of 3D printing for criminal purposes. Already it is possible to use consumer hardware to scan an object – for example a model of Mickey Mouse – and to 3D print a plastic replica. Just as mp3 files and the Internet had a massive impact on the music industry, so 3D printing looks set to alter how future intellectual property rights may or may not be defended.

More worryingly, it is already possible to 3D print working weapons. At present, a $230 personal 3D printer can only make a single-use plastic gun. But when it becomes possible to domestically 3D print in metal, we may have a significant problem on our hands.

A final and potentially massive minefield associated with 3D printing and personal fabrication is health and safety. Today, almost all of the products we purchase are subject to strict production standards and testing, with manufacturers held liable for any accidents and injuries that arise if their products inappropriately break or malfunction. But who would be liable if, for example, your son or daughter downloaded a free toy from a social media website, printed it out, gave it to a friend, a part broke off, and the second child choked on the broken-off part and died? Would fault lie with the person who designed the object (possibly also a child), the social media website via which it was shared, the manufacturer of your 3D printer, the supplier of your printing consumables, or even yourself as the parent of the maker of a dangerous item? There is currently no good answer to this question. Yet it is the kind of conundrum that we will fairly soon be unable to ignore.

IN THE WORDS OF PIONEERS

The 3D Printing Revolution is – like any other – the product of the actions, energies and visions of those people who are brave enough to make it happen. Over the past few years I have had the privilege to interview many such pioneers, and throughout this book I will divulge what they have told me and exactly what they are accomplishing. But right now, in this chapter, my goal is to capture your imagination rather than to focus on too many details and practicalities (we do, after all, have the rest of the book for that). So, as we head toward the end of this introductory chapter, I thought I would report the responses of just a few 3D printing pioneers when I asked them the fundamental question 'why 3D print?'.

One of the first people I spoke to was Anssi Mustonen, who runs a 3D printing and design company in Finland called AMD-TEC. For Anssi, the reason to 3D print is to allow customer service to be maintained. As he explained:

> We live in a hectic world and for me 3D printing is almost the only way to serve my clients as well as I can. For prototyping I don't have time to program [CNC machines] and I don't have time to send quotations to machining companies to get parts. 3D printing is not the only way to make parts, but it's faster when creating complex shapes and configurations than traditional methods.

Constantine Ivanov is the co-founder and CEO of 3DPrintus.ru in Russia, and told me how 3D printing is allowing him to deliver radically new kinds of products and services. As he enthused:

> 3D printing allows us to deliver solutions that are at a crossroads between manufacturing and the digital technology of the Internet. Our customers are discovering how easy it is to create and produce almost anything. I'm sure that the most important benefit for customers is the opportunity to use a simple interface to obtain a personalized product.

Over in the UK, Gary Miller – Managing Director of the 3D Print Bureau – told a similar story, if one tinged with a realistic note of caution. To quote Gary:

> We should 3D print because it's quicker – lead times are reduced – and we can achieve any geometry, almost! I started [using Objet 3D printers] over ten years ago, [and then] I had one material. The years have passed and now I've got over 2,000 materials to print with. So just imagine where we'll be in ten years' time. This said, however many materials you have, it's about placing those materials in the right hands. It's up to users to find the right applications. We need to keep expectations level, because the hype is too much. People need to use their expertise in their industry to find where the applications are right, and where it will add value and make their lives easier.

> A few years ago I was sceptical that 3D Printing would move into manufacturing, [but] in the first half of 2016 we have seen movement and increased orders for manufacturing. It's exciting to see where 3D Printing moves to next and what materials develop.

One of the most interesting, formal conversations I have ever had about 3D printing was with Jon Cobb, who is the Executive Vice President of Corporate Affairs for 3D printing giant Stratasys in the United States. Soon after we started talking, Jon focused in on the potential of 3D printing to change product design and distribution:

> So much of the emphasis with 3D printing is about adapting it to our traditional manufacturing processes, and to me it's really more about changing the fundamentals of design, which then allows you to change the way products are manufactured, and then that really starts to effect distribution as well. So you may imagine having a plumbing problem at home. And you take a picture of it on your iPhone, you send the problem to Home Depot, and then you walk in an hour or two later to collect a custom part that you didn't have to go through a wide variety of parts bins to locate. This is maybe two or five years down the road, but you can see it starting to happen.

Miranda Bastijns is Director of the Belgium-based 3D printing service i.materialise, and focused in on new kinds of market opportunity from yet another perspective. As she explained:

> 3D printing helps create a world where the products we buy have a better fit, a better match to one's personal style, and where we all have the ability to own something that is truly unique. For consumers, it is exciting that individuals can now not only create products that better serve their own needs and interests, but also start to sell the result to others like them. For example, a jewelry designer can offer their latest ring to a global audience and test the demand for the design. If there are no orders, no problem – and if there are, then the rings will be printed, delivered to the customer, and the designer will receive their share of the profit.

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Also recognising the potential of 3D printing to make products with a 'better fit' is Lucy Beard, the founder and 'chief visionary' for Feetz. This is a 'digital cobbler' that is already using 3D printers to make shoes that are individually fabricated-to-measure. As Lucy told me:

> 3D printing is allowing us to change how we make and consume products. In particular, the use of 3D printing means that we can make personalized products sustainably and recycle things more easily.

What Lucy and her team are doing over at Feetz.com really is amazing, and we will look at their work in more depth in chapter 4.

Marc Saunders is the Director of Global Solutions Centres at direct metal 3D printer manufacturer Renishaw. Like Miranda and Lucy, when asked why we should 3D print, he also focused on the opportunities that it can offer to manufacturers. As he explained:

> More and more companies are seeking to exploit the potential . . . to improve product performance, making products more efficient and better adapted

> to their application. [The technology's] unique ability to create complex geometries from high performance materials offers huge scope for innovation in both product design and business models. We expect additive manufacturing to play an increasing role in further unlocking process and product improvements to deliver exceptional value.

Finally Sylvain Preumont – the founder and Executive Chairman of the iMakr 3D printer stores and the My Mini Factory 3D content website – noted how 3D printing will free the imagination. As he told me:

> The wide availability of 3D printing will unleash creativity, because people will be able to invent, design and make in almost no time at low cost. They'll also be able to download curated content that is ready to print, and easy to adapt to their own needs and personality. Tomorrow's children will ask "is it true that when you were young you didn't have a 3D printer?"

THE ADDITIVE FRONTIER

As the words of Anssi, Constantine, Gary, Jon, Miranda, Lucy, Marc and Sylvain make very clear, 3D printing continues to evoke a powerful passion among its most ardent pioneers. Following the hype bubble of 2012 and 2013, the 3D printing industry is also stronger than ever before. Not least, since 2013, many large, traditional manufacturers have chosen to *enter* the 3D printing marketplace, and this has to be a very positive signal.

Nobody can tell you the future of 3D printing. Yet I think we now have very strong grounds to believe that it is going to have a radical, transformational impact across many manufacturing sectors. Right now, most 3D prints are still prototypes. But in a lot less than a decade this is no longer going to be the case. Indeed, by 2020, it is highly likely that tens of millions of people will have flown on an aircraft that has 3D printed components, will have been fitted with a 3D printed dental appliance, will have worn a pair of shoes with some 3D printed parts, and will have been 3D scanned and 3D printed as a figurine for somebody's mantlepiece.

My intention in the rest of this book is to explore and explain the world of 3D printing in as down-to-earth a manner as possible. To this end I will be including as many specific examples as I can, with these based on supplier information, case studies, company reports, interviews, and other sources that most people would reasonably consider as 'fact'. Inevitably, I will also offer some of my own insight and opinion, with my primary occupation as a futurist rising to the fore in parts of our last two chapters. But my main intention is to provide you – my valued reader – with as much factual information as possible so that you can decide for yourself whether or not 3D printing really is the next industrial revolution. This said, I do hope that you will end up agreeing with me that it is.

THE REST OF THE BOOK

The remaining contents of this book are as follows: